# The SLoWPoKES Catalog of Low-mass Ultra-wide Binaries: A Cool Stars Resource for Testing Fundamental Properties and for Constraining Binary Formation Theory

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We present results from the Sloan Low-mass Wide Pairs of Kinematically Equivalent Stars (SLoWPoKES) catalog of ultra-wide ($10^{3-5.5}$ AU), low-mass (K5–M7) common proper motion binaries. We constructed a Galactic model, based on empirical stellar number density and 3D velocity distributions, to select bona fide pairs with probability of chance alignment <5%, making SLoWPoKES an efficient sample for followup observations. Our initial catalog contains 1342 disk dwarf, subdwarf, and white dwarf–red dwarf systems and is the largest collection of low-mass, wide binaries ever assembled. The diversity—in mass, metallicity, age, and evolutionary states—of SLoWPoKES pairs makes it a valuable resource of *coeval laboratories* to examine and constrain the physical properties of low-mass stars. SLoWPoKES pairs show signatures of two (or more) formation modes in the distribution of the physical separation and higher-order multiplicity. Neither dynamical dissipation of primordial triples/quadruples or dynamical capture of ejected stars can explain the observed populations by itself. We use followup spectroscopic observations to recalibrate the metallicity-sensitive $\zeta_{\rm TiO/CaH}$ index by assuming that both members of the binary system have the same composition. Our new formulation is a significantly better tracer of absolute metallicity, particularly for the early-type M dwarfs. The catalogs are publicly available on a custom data visualization portal.





## 1 Introduction

Often times it is the extremes of a distribution that encode the most valuable information about the underlying physics. While typical binary star separations are $\sim$30 AU (e.g., Duquennoy & Mayor 1991; Fischer & Marcy 1992), a large number of ultra-wide binary systems ($\geq 10^{3-5}$ AU) have been identified in star-forming regions (e.g., Connelley, Reipurth & Tokunaga 2008; Kraus & Hillenbrand 2009b) and in the field (e.g., Chaname & Gould 2004; Lépine & Bongiorno 2007; Dhital et al. 2010). While these ultra-wide systems make up $\leq$10% of all binaries, they have uniquely interesting and valuable roles as boundary conditions to the star formation process. From detailed numerical simulations, we now know star formation to be a dynamic process where cores and protostars interact with each other and modify the environments (e.g., Bate 2009). Therefore, how these wide binaries are formed has important implications on our understanding of the entire star formation process as well as that of the sub-structure in star-forming regions and how the field gets populated with single and binary stars. In addition, whether planets can be formed and/or can survive in such dynamically active environments is an important question. Wide pairs are important coeval laboratories, and understanding their origins informs us about the validity of their coevality (e.g., Stassun, Mathieu & Valenti 2007; Kraus & Hillenbrand 2009a) and iso-metallicity (e.g., Lépine, Rich & Shara 2007; Dhital et al. 2012) assumptions.

We have assembled the Sloan Low-mass Wide Pairs of Kinematically Equivalent Stars (SLoWPoKES) catalog of wide, low-mass common proper motion binary systems; the selection is briefly described in Section 2. We have identified signatures of two (or more) formation modes in the physical separation and higher-order multiplicity distributions of SLoWPoKES systems, which we describe in Section 3. In Section 4 we present followup spectroscopic observations of SLoWPoKES systems to verify and refine the low-mass metallicity index, $\zeta_{\rm TiO/CaH}$. We have created a web portal for data visualization and dissemination, which we describe in Section 5. We provide a synopsis of our ongoing and future work in Section 6.

## 2 Construction of the SLoWPoKES Catalog

We searched for common proper motion companions around low-mass dwarfs (spectral type of K5 or later) in

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the Sloan Digital SKy Server (SDSS) Data Release 7 photometric catalog (Abazajian et al. 2009). By matching photometric distances (Bochanski et al. 2010) and SDSS/USNO-B proper motions (Munn et al. 2004), we identified candidate systems with angular separations of 7–180″. A series of quality cuts on the photometry and the proper motions were made to ensure the resultant sample was not contaminated. See Dhital et al. (2010) for details.

False positives are inherent in such statistical samples, arising from chance alignments within the uncertainties of the selection criteria. The probability of such a chance alignments increases with the separation of the candidate companion as well as with the distance to the star. Therefore, for a pure sample of physically associated CPM pairs to be constructed, a detailed analysis of the probability of chance alignment need to be conducted. We constructed an Monte Carlo-based Galactic model using empirical stellar number density (Juric et al. 2008; Bochanski et al. 2010) and 3D velocity distributions (Bochanski et al. 2007). Each iteration of the model repopulates a $30' \times 30'$ conical volume extending to 2500 pc and centered on the primary of each candidate system and assigns a 3D velocity to each star. As only single stars are included in this model galaxy, any star with matching position and proper motions to the primary of the candidate system is a chance alignment. The probability of chance alignment ($P_f$) is then, simply, how many times such matches were found in $10^5$ iterations. Only pairs with $P_f \leq 5\%$ were included in the SLoWPoKES catalog. Thus, SLoWPoKES contains only bona fide binary systems, making it an ideal source for followup observations. A total of 1342 common proper motion binaries, comprising of GK–M dwarf, M dwarf, M subdwarf, and white dwarf–M dwarf systems, were identified. They span a wide range in mass, mass ratio, metallicity, and evolutionary states.

Radial velocities from followup spectroscopic observations have confirmed the physical association of observed SLoWPoKES pairs (Dhital et al. 2012).

## 3 Multiple Modes for Formation of Wide Binaries

Figure 1 shows the distribution of projected physical separations and total system mass (inferred from their $r - z$ colors) for SLoWPoKES systems. There is a distinct bimodality, with a break at ∼20,000 AU. This is notably the same scale as the substructure found in star-forming regions and open clusters (CartWright & Whitworth 2004). When compared with dissipation time scales of wide binaries (Weinberg, Shapiro & Wasserman 1987), the bimodality is suggestive of (i) a “wide” population that is dynamically stable over >10 Gyr and (ii) an “ultra-wide” population of young, loosely-bound systems that will dissipate in ∼1–2 Gyr (Dhital et al. 2010). There are two scenarios that explain this bimodality:

1. *Ultra-wide binaries generally form as hierarchical triples and quadruples in a similar manner as other binary systems and with similar separations.* The outer orbit then gets wider by transferring angular momentum from inner obit (e.g., Tokovinin 1997). Once the orbit is larger than a few thousand AU, further energy transfer under the influence of Galactic tides, giant molecular clouds, and other stars can take place, widening the system to their current observed separations, until it eventually dissipates (Weinberg et al. 1987; Jiang & Tremaine 2010). A high multiplicity fraction among wide binaries is a requisite in this scenario, which further predicts that the widest pairs will be most likely to contain a third (or fourth) companion.
2. *As suggested by recent numerical simulations, as stars are dynamically ejected from their parental cloud core, a small fraction will get bound and form ultra-wide systems* (Bate & Bonnell 2005; Kouwenhoven et al. 2010; Moeckel & Bate 2010; Moeckel & Clarke 2011). Ultra-wide systems thus formed via dynamical capture would preferentially be low-mass but not necessarily have an enhanced hierarchical multiplicity. Separations need to be less ∼50–80 AU to have survived the dynamical ejection from its natal cloud core (Parker & Goodwin 2010).

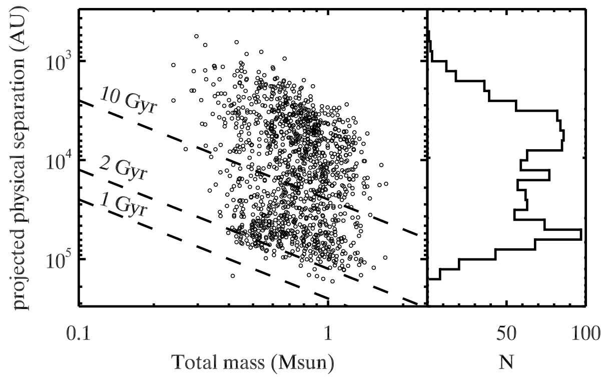


**Fig. 1** Projected physical separation vs. total mass (inferred from $r - z$ colors) for the M dwarf pairs in SLoWPoKES. Dashed lines represent the timescales of dynamical dissipation of binaries (Weinberg et al. 1987). The distribution shows two populations of wide binaries, suggesting that they were either formed differently or have gone through vastly different dynamical sculpting.

Given that we only know the projected orbital parameters of these very wide systems, discriminating between even such radically different formation scenarios is not an easy task. Ensemble properties, preferably ones that are not dependent on the projection angle, of a statistically significant sample are needed. Hence, the key discriminant between the two scenarios is the frequency and arrangement of triples and quadruples among wide binaries.

In a high-resolution imaging study using the Laser Guide Star with Adaptive Optics at the Keck and Palomar telescopes, we found 45% of the observed wide binaries were hierarchical triples and quadruples (Law et al. 2010). Moreover, as shown in the left panel of Figure 2, the mul-

 

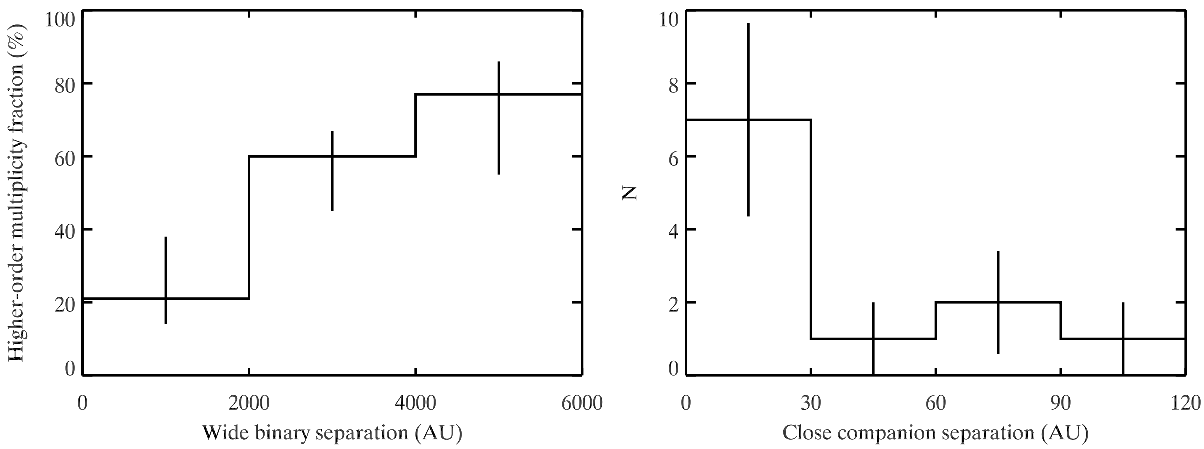


**Fig. 2** *Left:* The higher-order multiplicity fraction increases as a function of wide binary separation, suggesting that wide binaries form through dynamical widening of primordial triples/quadruples. *Right:* The distribution of physical separations of the close binaries is consistent with them having been ejected from clusters and getting bound to another ejected star to form a wide binary. (Reproduced from Law et al. (2010).)

tiplicity fraction increased from 20% at the closest wide binary separations probed (∼1000 AU) to 80% at the largest (∼5000 AU), with 2-$\sigma$ significance. For the widest binaries, the multiplicity fraction is also significantly higher than the binary fraction observed for isolated low-mass stars in the field (34–42%; Fischer & Marcy 1992; Reid & Gizis 1997). So while the binaries of up to ∼1000 AU could have formed via a mechanism similar to other field stars, wide binaries seem to have formed differently. The enhanced multiplicity is indicative of a populations formed largely via dynamically dissipation.

Figure 2 (right panel) shows the orbital separations of the inner binaries in our sample. The distribution peaks sharply at <30 AU; moreover, only one system at physical separation of >80 AU, the nominal limit for a binary to survive a dynamical ejection (Parker & Goodwin 2010). This distribution is consistent with a population that was formed via dynamical ejection followed by capture.

In conclusion, our data do not rule out either scenario of wide binary formation but indicate neither mechanism can form all of the observed wide binaries. A larger sample is needed to confirm our 2-$\sigma$ result of increasing multiplicity with wide binary separation, as well as to probe systems of lower masses and larger separations. We conclude that multiple processes, not all of which are primordial but are likely to be dynamical in nature, are likely responsible for the observed distribution of stellar binaries.

## 4 A Refined Metallicity Index for M Dwarfs

While spectral modeling has allowed for metallicity determinations and well-defined metallicity indices for warmer stars, such efforts in the late-K and M spectral type regimes (e.g., Hauschildt, Allard & Barron 1999) have met with notable problems due to the onset of broad molecular lines at

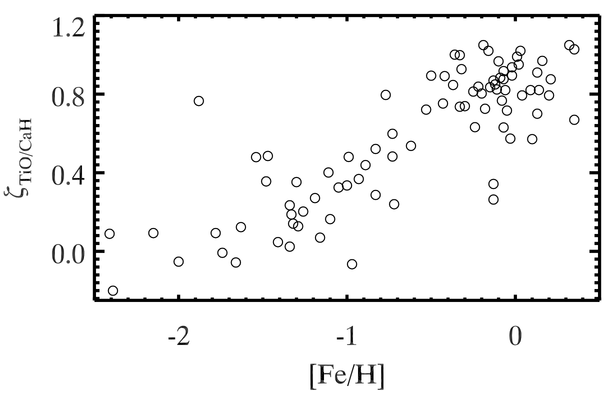


**Fig. 3** The relative metallicity indicator, $\zeta_{\rm TiO/CaH}$ from Dhital et al. (2012), vs. the absolute metallicity, [Fe/H], from Woolf et al. (2009). The refined definition of $\zeta_{\rm TiO/CaH}$ yields a tighter $\zeta_{\rm TiO/CaH}$–[Fe/H] relation but still suffers from considerable scatter.

<4300 K and due to incomplete molecular line lists. Hence, the metallicity of low-mass stars remains an elusive parameter to measure. While near-infrared indices (Rojas-Ayala et al. 2010; Terrien et al. 2012) will likely lead to accurate metallicity estimates, their scope is limited as it is not practical to acquire near-infrared spectra for large samples of low-mass stars. However, as the most numerous stellar constituents, M dwarfs are the best tracers of the formation, chemical, and dynamical history of the Milky Way. So having an easily observable index tied to an absolute metallicity scale is imperative. The $\zeta_{\rm TiO/CaH}$ index (Lépine et al. 2007) is ideal for such a purpose as it can be measured from moderate-resolution optical spectra.

From follow up spectra of 113 SLoWPoKES pairs, we found that the $\zeta_{\rm TiO/CaH}$ values for components of a binary are consistent with each other, within the error bars, for most

pairs (Dhital et al. 2012). However, $\zeta_{\mathrm{TiO/CaH}}$ is systematically overestimated for higher-mass M dwarfs. Leveraging the iso-metallicity of components of a pair, we redefined $\zeta_{\mathrm{TiO/CaH}}$ by minimizing $\Delta\zeta_{\mathrm{TiO/CaH}}$. While the change in the definition is small, it is much more consistent with iso-metallicity loci that is defined by the observed binaries.

With our new definition of $\zeta_{\mathrm{TiO/CaH}}$, we also recalibrated the absolute $\zeta_{\mathrm{TiO/CaH}}$–[Fe/H] relation from Woolf, Lépine & Wallerstein (2009), calibrated using a sample of FGK–M binaries. As Figure 3 shows, there is a definitive linear relation between the relative metallicity indicator, $\zeta_{\mathrm{TiO/CaH}}$, and the absolute metallicity, [Fe/H]. However, there remains a considerable scatter. We have conducted observations of low-metallicity and lower-mass binaries to further calibrate the $\zeta_{\mathrm{TiO/CaH}}$–[Fe/H] relation.

## 5 A Web-based Data Visualization Portal for Low-mass Dwarfs

We have created a new web-based data visualization portal, which is hosted on a dedicated web server at Vanderbilt University[1]. The purpose of this portal is twofold: (i) provide easy access to large data catalogs of low-mass stars and (ii) allow for easy and fast visualization of the data without needing to download the entire catalog. We have also created tools to plot the data on the web browser, to do target selection for follow-up observations, and to cross-match user-inputted objects with the catalogs. Images and web links for the SDSS and 2MASS photometric and, when available, SDSS spectroscopic data are also included. Currently, the server hosts four different data sets based on the SDSS survey: the SLoWPoKES binaries (Dhital et al. 2010), the white dwarf–M dwarf binary sample (Morgan et al. 2012), and the SDSS spectroscopic samples of M (West et al. 2011) and L dwarfs (Schmidt et al. 2010). This web portal is meant to be a public, live catalog, so all followup data will be made available as well.

## 6 Future Work

In Dhital et al. (2010) we noted that for small angular separations, proper motions are not required to identify binary systems with a high level of fidelity. Our Galactic model is able to effectively sift out the chance alignments to $\sim 15''$. We have thus identified $\sim$80,000 binary systems with separations of 0.4–15$''$ and probability of chance alignment $\leq$5% (SLoWPoKES-II; Dhital et al. *in preparation*).

The SLoWPoKES catalog has already enabled many programs that use the pairs as coeval laboratories to explore the fundamental proeprties of low-mass stars. Ongoing studies include measuring absolute metallicity (Dhital et al. 2012; Bochanski et al. *in preparation*), intrinsic scatter in activity (Gunning et al. *in preparation*), and ages of M dwarfs using gyrochronology or cooling ages of white dwarfs (Morgan et al. *in preparation*). With a much larger and more diverse SLoWPoKES-II catalog, more follow up observations should be enabled.

[1] `http://slowpokes.vanderbilt.edu`

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